

Anisotropy of the low-temperature magnetostriction of $\text{Sr}_3\text{Ru}_2\text{O}_7$

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We use high-resolution capacitive dilatometry to study the low-temperature linear magnetostriction of the bilayer ruthenate $\text{Sr}_3\text{Ru}_2\text{O}_7$ as a function of magnetic field applied perpendicular to the ruthenium-oxide planes ($B \parallel c$). The relative length change $\Delta L(B)/L$ is detected either parallel or perpendicular to the c -axis close to the metamagnetic region near $B = 8$ T.

In both cases, clear peaks in the coefficient $\lambda(B) = d(\Delta L/L)/dB$ at three subsequent metamagnetic transitions are observed. For $\Delta L \perp c$, the third transition at 8.1 T bifurcates at temperatures below 0.5 K. This is ascribed to the effect of an in-plane uniaxial pressure of about 15 bar, unavoidable in the dilatometer, which breaks the original fourfold in-plane symmetry.

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1 Introduction The bilayer ruthenate $\text{Sr}_3\text{Ru}_2\text{O}_7$ has recently attracted much interest, because of itinerant electron metamagnetism and the possible formation of a nematic electron fluid close a quantum critical point near 8 T for fields applied perpendicular to the ruthenium-oxide planes, i.e. parallel to the tetragonal c -axis [1,2,3,4]. Early studies of the magnetic susceptibility of single crystals have suggested quantum criticality to arise from the suppression of the critical temperature of a first-order metamagnetic transition by tuning the field angle towards $B \parallel c$ [2]. Subsequent studies on high-quality single crystals ($\rho_0 = 0.4 \mu\Omega\text{cm}$) have revealed a fine structure in the T - B phase diagram, bound by two metamagnetic transitions at 7.85 and 8.07 T which are of first-order for temperatures below 0.7 and 0.5 K, respectively [3,5]. Within this regime, the electrical resistivity peaks and becomes temperature independent, indicating an increase of elastic scattering, possibly due to the formation of some kind of domains [3], whereas outside this region the thermal expansion behavior was found to be compatible with metamagnetic quantum criticality [6]. An in-plane anisotropy of the electrical resistivity arises when the applied magnetic field is tilted by 13° off the c -axis, indicating a spontaneously

broken fourfold rotational symmetry in the ab plane perpendicular to the c -axis [4]. The coupling of this presumed "electronic nematic state" to the lattice could be studied most sensitively by capacitive dilatometry. Previously, a strong magnetoelastic coupling with highly enhanced magnetic Grüneisen parameter has been found in linear magnetostriction measurements along the c -axis in $\text{Sr}_3\text{Ru}_2\text{O}_7$ [3,7]. Since in the novel phase the four-fold symmetry is broken, length measurements perpendicular to the c -axis are of particular interest. In this paper, we compare for $B \parallel c$ the magnetostriction along and perpendicular to the c -axis.

2 Experiment For our experiments, we have used one piece of about $(1.5 \text{ mm})^3$ dimension of the same high-quality single crystal, grown by floating zone technique [8], which has been studied previously in thermal expansion and magnetostriction along the c -axis [3,6,7] (the original crystal has broken in two pieces). The magnetostriction has been determined by a miniaturized capacitive dilatometer, which is small enough to be mounted in parallel and perpendicular configuration in a dilution refrigerator with 18 T superconducting magnet. For our measurements, we have applied the field parallel

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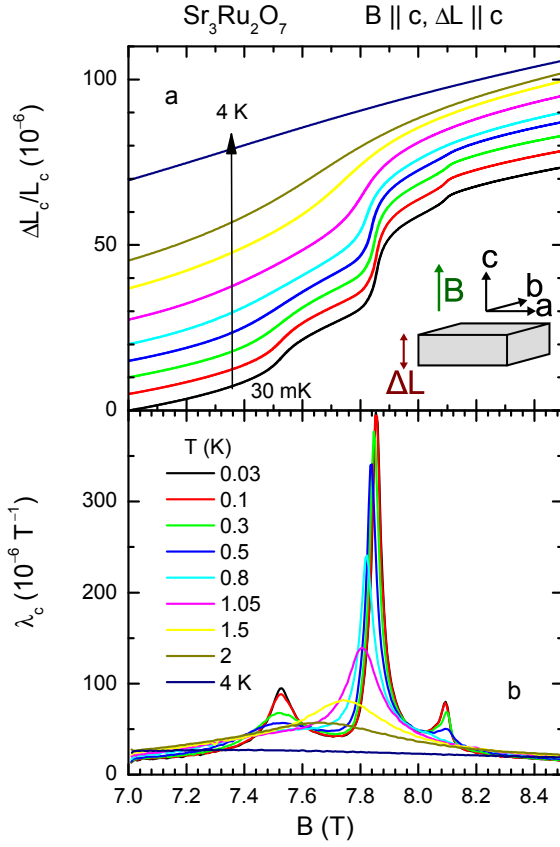


Figure 1 a: Linear magnetostriction $\Delta L_c/L_c$ along the c -axis of $\text{Sr}_3\text{Ru}_2\text{O}_7$ measured at various temperatures for $B \parallel c$, as indicated in the sketch. b: Respective magnetostriction coefficient $\lambda_c(B)$.

to the c -direction, similar as previously. The linear magnetostriction has been detected in two separate runs first parallel to the applied field, i.e. $\Delta L \parallel B \parallel c$ as sketched in Figure 1a, and subsequently perpendicular to the field, $\Delta L \perp B \parallel c$ (Fig. 2a)¹. The magnetic field is varied with a rate of 1 T/h for temperatures between 30 mK and 4 K. No hysteresis larger than 2 mT could be detected similar as previously [7]. The magnetostriction coefficient $\lambda = d(\Delta L/L)/dB$ has been obtained by linear fits on 20 mT field intervals.

3 Results The length change parallel to the field and to the c -axis, $\Delta L_c/L_c$ between 7 and 8.5 T, displayed in Figure 1a, is similar as observed previously [3, 7]. However, the three peaks in the coefficient $\lambda_c(B)$ are narrower and larger, indicating sharper transitions in this piece of the original single crystal used in [3, 7]. This may be related to the first-order nature of the metamagnetic transitions. The height of λ_c at the central peak saturates at low- T , simi-

¹ The sample edges are parallel to the axes of the pseudotetragonal crystal structure with $a \approx b \approx 3.89 \text{ \AA}$ [9].

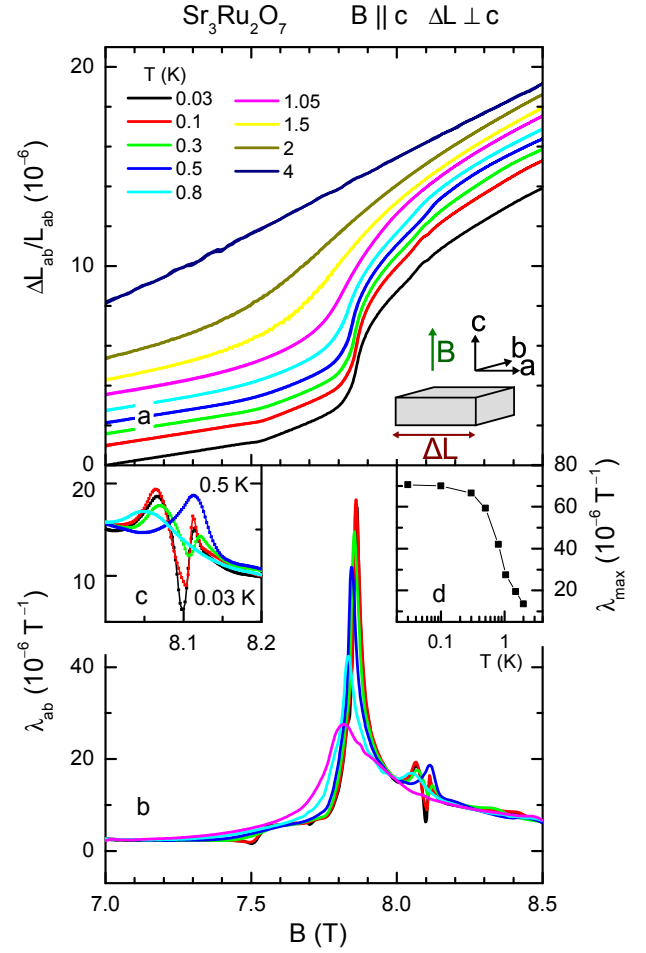


Figure 2 a: Linear magnetostriction $\Delta L_{ab}/L_{ab}$ of $\text{Sr}_3\text{Ru}_2\text{O}_7$ measured perpendicular to the c -axis at various temperatures for $B \parallel c$, as indicated in the sketch. b: Respective magnetostriction coefficient $\lambda_{ab}(B)$. Inset c enlarges region close to upper metamagnetic transition. Inset d displays temperature dependence (on a log scale) of maxima in λ_{ab} at the central metamagnetic transition.

lar as found previously [7] and similar as observed for λ_{ab} (inset d of Fig. 2).

Figure 2 shows corresponding magnetostriction results transverse to the applied field. In this configuration, the length change $\Delta L_{ab}/L_{ab}$ between 7 and 8.5 T is about five times smaller compared to the former case. The central peak in λ_{ab} is qualitatively similar as found for λ_c , including its temperature dependence. However, the two other metamagnetic transitions display very different signatures. The 7.5 T crossover is visible as a distinct *minimum* in $\lambda_{ab}(B)$ at lowest temperatures. Furthermore, a splitting of the 8.1 T transition is observed below 0.5 K, resulting in a sharp minimum close to 8.1 T in $\lambda_{ab}(B)$ at lowest temperatures (cf. inset c of Fig. 2). As discussed be-

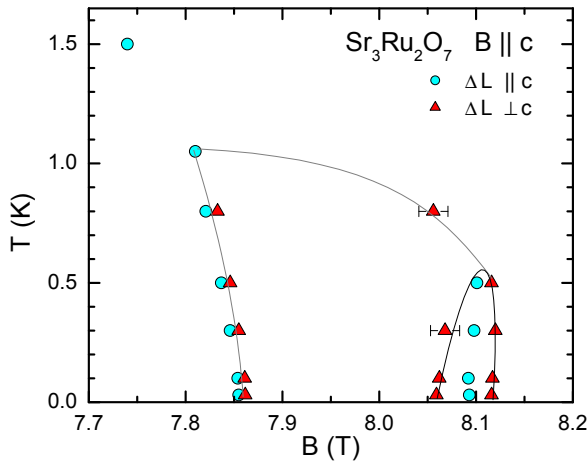


Figure 3 T - B phase diagram for $\text{Sr}_3\text{Ru}_2\text{O}_7$, $B \parallel c$. Blue circles and red triangles indicate positions of maxima in λ_c and maxima and minima in λ_{ab} . Black and gray lines indicate bifurcation of 8.1 T transition in λ_{ab} measurement and boundary of proposed symmetry-broken phase [3], respectively.

low, we ascribe this anomaly to the small uniaxial pressure generated by our dilatometer.

Figure 3 displays a T - B phase diagram with the positions of maxima in the linear magnetostriction coefficients $\lambda_{ab}(B)$ and $\lambda_c(B)$ indicated by blue circles and red triangles, respectively. Besides the bifurcation of the 8.1 T peak for measurements perpendicular to the c -axis at temperatures below 0.5 K, we also note the small shift of the central peak towards larger B for this configuration.

4 Discussion The sign of the linear magnetostriction is related by the Maxwell relation $\lambda V_m = -(dM/dP)_{P \rightarrow 0}$ to the uniaxial pressure dependence of the magnetization (V_m : molar volume). Since $\lambda > 0$ for both orientations for the main metamagnetic transition, the magnetization decreases with increasing pressure, in qualitative agreement with the shift of the metamagnetic field under hydrostatic pressure [10].

Positions of transitions in T - B phase space can generally not depend on the direction along which magnetostriction has been measured (for similar field orientation). Since the *same* crystal has been used, the only reason for the observed differences in the positions of the metamagnetic transitions is the effect of a weak uniaxial pressure in these measurements. The two parallel flat springs of our dilatometer exert a force of approximately 3 N on the samples cross-section along the measurement direction, corresponding to a uniaxial pressure of roughly 15 bar for the studied crystal. Using the estimated uniaxial pressure dependence of the central metamagnetic transition [7], this pressure causes a shift of approximately 0.01 T, only,

which is of similar size as a possible field offset due to remanence in the superconducting magnet. However, for the λ_{ab} measurements the uniaxial pressure acts *perpendicular* to the c -axis and therefore breaks the fourfold in-plane symmetry. Such symmetry breaking could have a strong effect on the low- T properties. Most interestingly, the 8.1 T transition is found to bifurcate below 0.5 K, i.e. at temperatures below which this metamagnetic transition is of first order [3]. The comparison with the magnetostriction experiments along the c -axis indicates that this splitting arises from the in-plane uniaxial pressure. Interestingly, a bifurcation of two metamagnetic transitions has also been found for a high-quality $\text{Sr}_3\text{Ru}_2\text{O}_7$ single crystal at $B \perp c$, for temperatures below 0.5 K [11]. In this case, the field applied perpendicular to the c -axis breaks acts symmetry breaking.

To summarize, we have studied the anisotropy of the low-temperature magnetostriction of $\text{Sr}_3\text{Ru}_2\text{O}_7$ by capacitive measurements along and perpendicular to the applied field $B \parallel c$. $\Delta L_c/L_c(B)$ is about five times larger than $\Delta L_{ab}/L_{ab}(B)$. Remarkably, we observe a splitting of the metamagnetic transition at 8.1 T for the measurement perpendicular to the c -axis that is ascribed to a symmetry breaking uniaxial pressure of about 15 bar in this experiment.

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